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ICRF3, the new realization of the International Celestial Reference Frame

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on behalf of the
ICRF3 Working Group



ICRF3 Working Group

IAU Working Group formed in 2012 to generate ICRF3
for presentation at IAU 2018 General Assembly

P. Charlot (Chair)	A. L. Fey	Z. Malkin
E. F. Arias	R. Gaume	A. Nothnagel
D. Boboltz	D. Gordon	M. Seitz
J. Boehm	R. Heinkelmann	E. Skurikhina
S. Bolotin	C. Jacobs	J. Souchay
G. Bourda	S. Lambert	O. Titov
A. de Witt	C. Ma	

2012-2015: WG chaired by C. Jacobs

2015-2018: WG chaired by P. Charlot



Outline

- Data sets and analysis work for ICRF3
- Comparison with ICRF2 and Gaia DR2
- Impact of Galactic aberration
- Summary

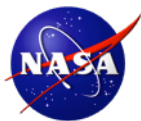


Data sets

ICRF3 incorporates data up to 2018 March 31

- **S/X band (8 GHz)**
 - All VLBI sessions available through IVS since 1979
 - Data from VLBA Calibrator Survey: VCS-I (1994-2007) and VCS-II (2014-2015)
 - Bi-monthly VLBA sessions acquired under USNO-time since 2017
- **K band (24 GHz)**
 - 54 VLBA sessions since 2002
 - including 20 under USNO-time since 2017
 - 15 Hartrao-Hobart single-baseline sessions since 2014
- **X/Ka band (32 GHz)**
 - 167 sessions carried out on the DSN (Goldstone/Tidbinbilla/Robledo), 10% of which also including the ESA Malargue station (Argentina)

In all about **12 million observations** (vs. 6.5 million for ICRF2)



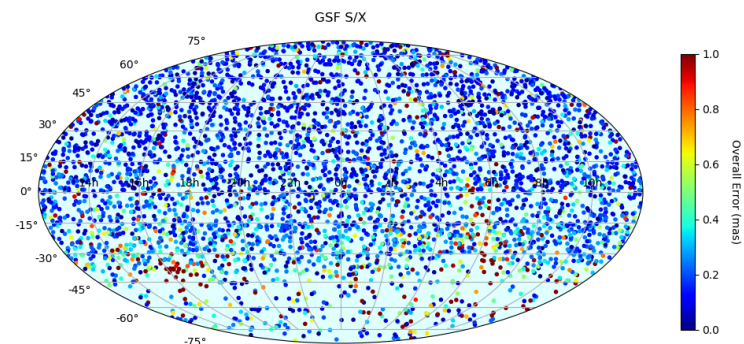
Analysis work

- Three rounds of ICRF3 prototype solutions accomplished
 - Submitted by 09/2016, 07/2017 and 01/2018
 - 9 solutions (using 6 different software packages) produced each time
 - One such solution provided to the Gaia Science Team in July 2017 to serve as input for defining the orientation of Gaia DR 2 frame.
- Numerous alternate solutions varying the modeling and analysis configuration to assess the level of systematic errors
 - Cutoff elevation angle, troposphere modeling, station positions
 - Special handling sources, ICRF2-ICRF3 transfer sources
 - Impact of new southern-hemisphere stations in Australia and NZ
 - Galactic aberration
- Extensive comparisons between different solutions (also with Gaia DR1 and DR2) essential to identify and resolve issues
- Final solutions being produced



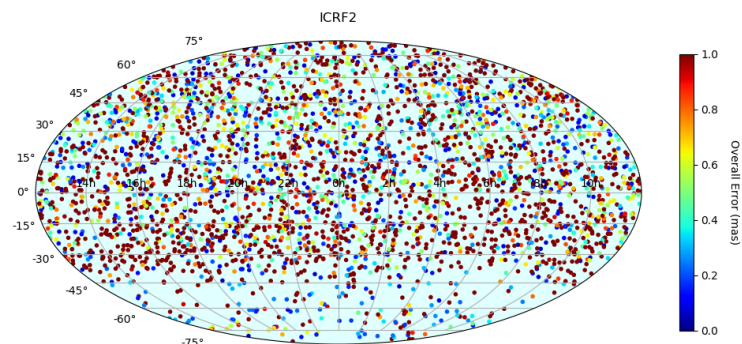
ICRF3 vs ICRF2

ICRF3 - S/X band



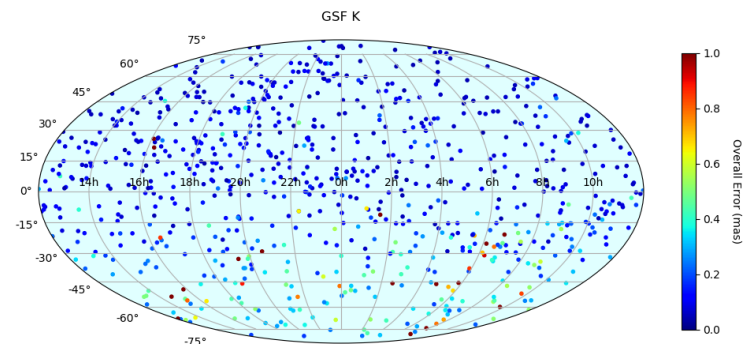
4359 sources

ICRF2



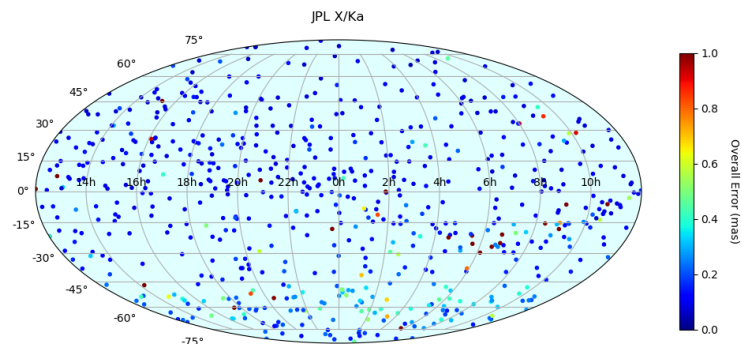
3414 sources

ICRF3 - K band



824 sources

ICRF3 - X/Ka band

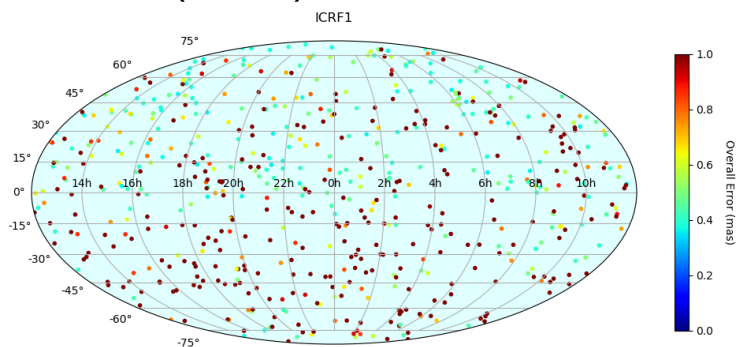


678 sources



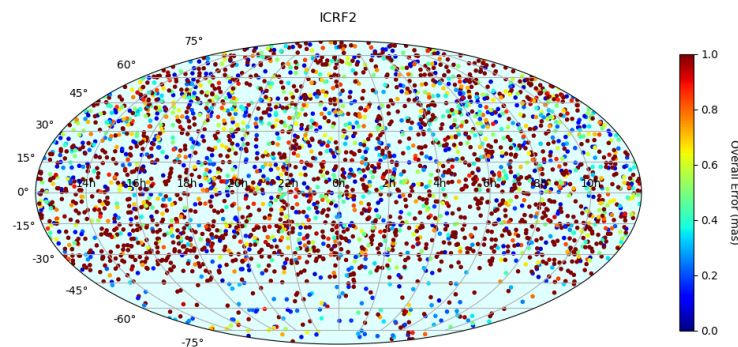
From ICRF1 to ICRF3 & Gaia DR2

ICRF1 (1998)



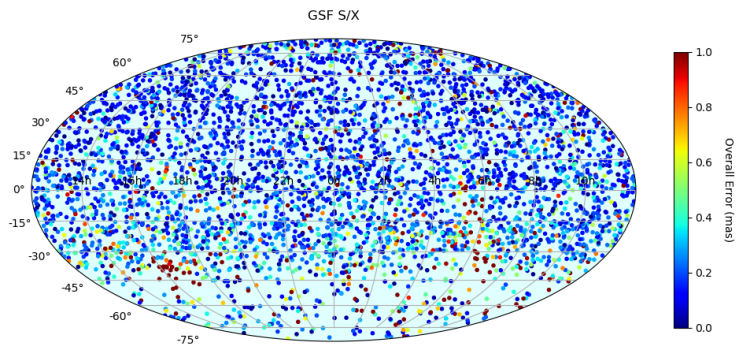
608 sources

ICRF2 (2009)



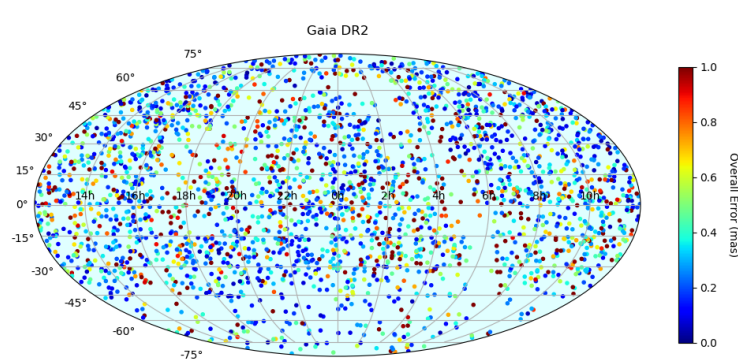
3414 sources

ICRF3 (2018)



4359 sources

Gaia DR2 (2018)



2820 common sources



Comparing catalogs

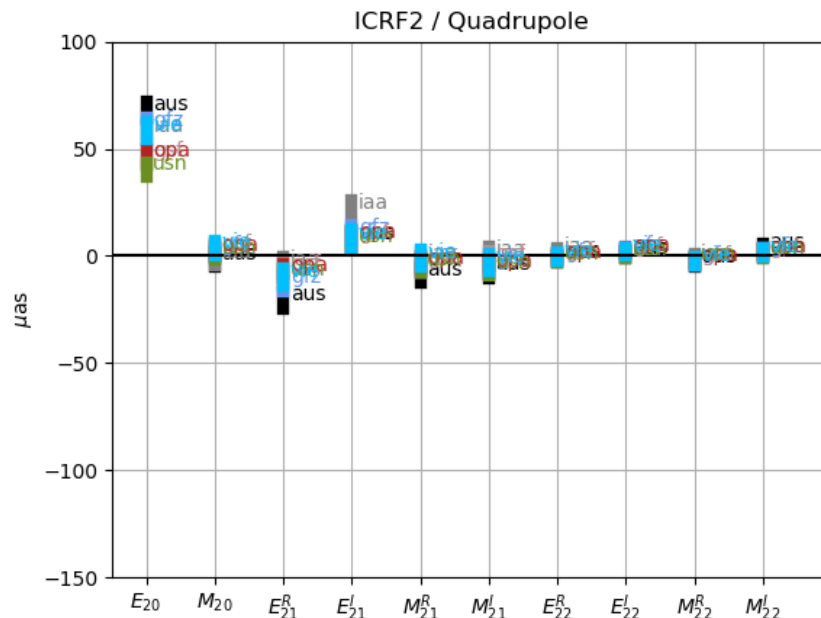
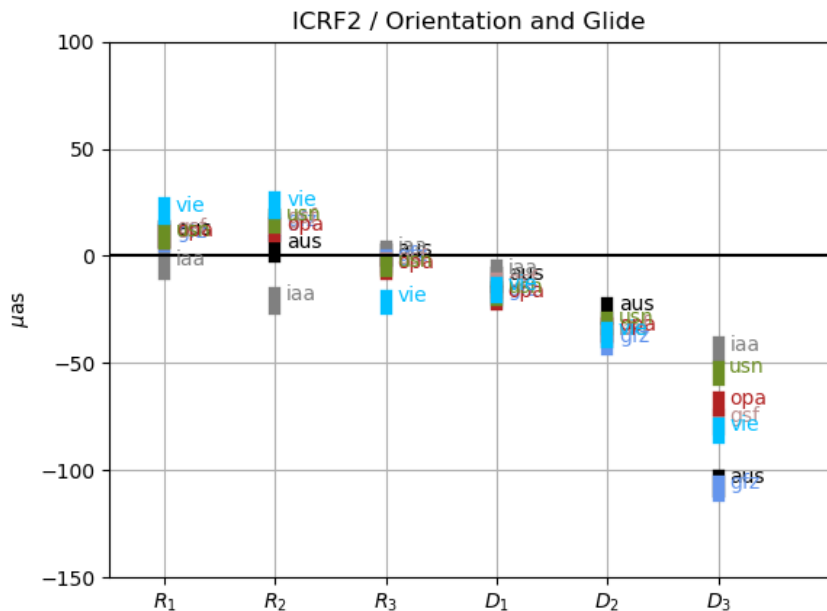
$$\begin{aligned}
 \Delta\alpha \cos \delta &= R_1 \cos \alpha \sin \delta - R_2 \sin \alpha \sin \delta - R_3 \cos \delta - D_1 \sin \alpha + D_2 \cos \alpha \\
 &+ a_{20}^M \sin 2\delta \\
 &+ \left(a_{21}^{E, \text{Re}} \sin \alpha + a_{21}^{E, \text{Im}} \cos \alpha \right) \sin \delta \\
 &- \left(a_{21}^{M, \text{Re}} \cos \alpha - a_{21}^{M, \text{Im}} \sin \alpha \right) \cos 2\delta \\
 &- 2 \left(a_{22}^{E, \text{Re}} \sin 2\alpha + a_{22}^{E, \text{Im}} \cos 2\alpha \right) \cos \delta \\
 &- \left(a_{22}^{M, \text{Re}} \cos 2\alpha - a_{22}^{M, \text{Im}} \sin 2\alpha \right) \sin 2\delta, \\
 \Delta\delta &= -R_1 \sin \alpha + R_2 \cos \alpha - D_1 \cos \alpha \sin \delta - D_2 \sin \alpha \sin \delta + D_3 \cos \delta \\
 &+ a_{20}^E \sin 2\delta \\
 &- \left(a_{21}^{E, \text{Re}} \cos \alpha - a_{21}^{E, \text{Im}} \sin \alpha \right) \cos 2\delta \\
 &- \left(a_{21}^{M, \text{Re}} \sin \alpha + a_{21}^{M, \text{Im}} \cos \alpha \right) \sin \delta \\
 &- \left(a_{22}^{E, \text{Re}} \cos 2\alpha - a_{22}^{E, \text{Im}} \sin 2\alpha \right) \sin 2\delta \\
 &+ 2 \left(a_{22}^{M, \text{Re}} \sin 2\alpha + a_{22}^{M, \text{Im}} \cos 2\alpha \right) \cos \delta
 \end{aligned}$$

Mignard & Klioner, A&A, 2012



Orientation/glide/quadrupole terms

Comparison of ICRF3 (S/X) and ICRF2



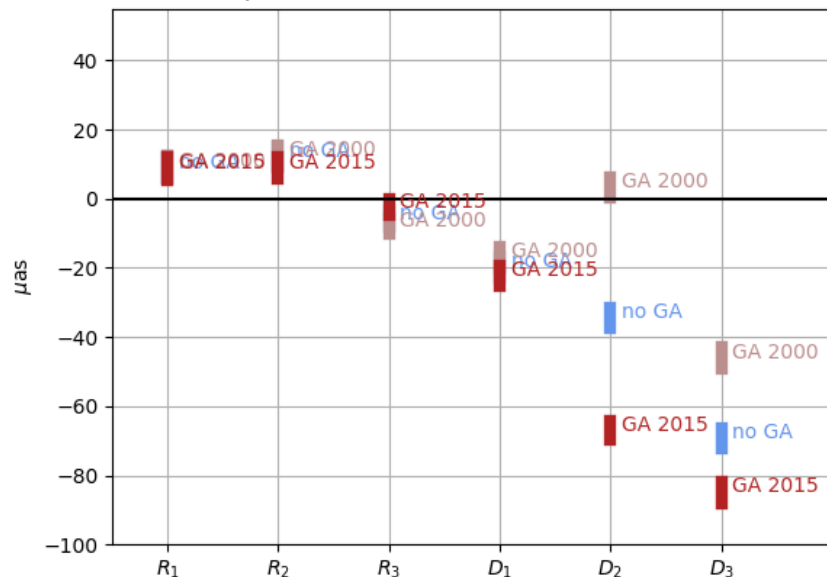
- 7 S/X solutions from different software packages/analysis centers
- All show similar deformations with respect to ICRF2 with significant glide parameters D2 and D3 and quadrupole term E20.



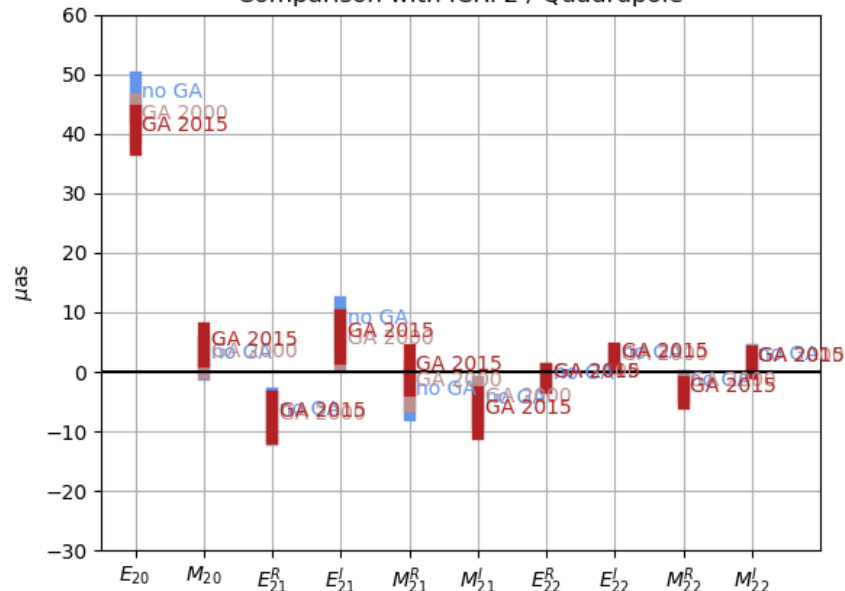
Effect of Galactic aberration

Impact of the reference epoch of the catalog

Comparison with ICRF2 / Orientation and Glide



Comparison with ICRF2 / Quadrupole



- 3 identical solutions (S/X) made by varying the reference epoch of the catalog (2000.0 or 2015.0) or with Galactic aberration not applied
- Applying/not applying Galactic aberration and changing the reference epoch has a significant impact on the glide parameters D_2 and D_3 .



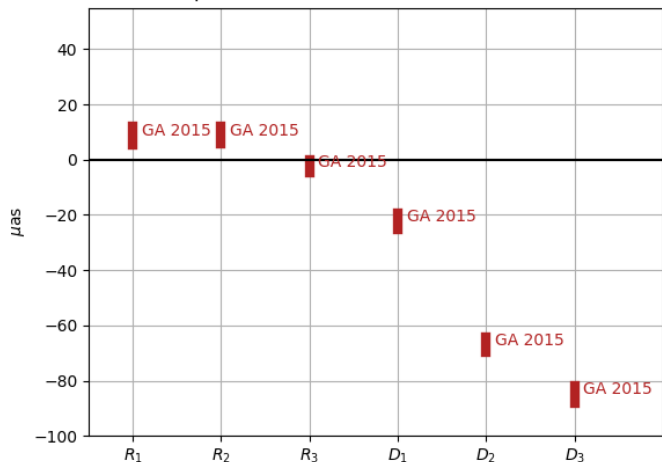
Comparing with ICRF2/Gaia DR2

Epoch 2015.0

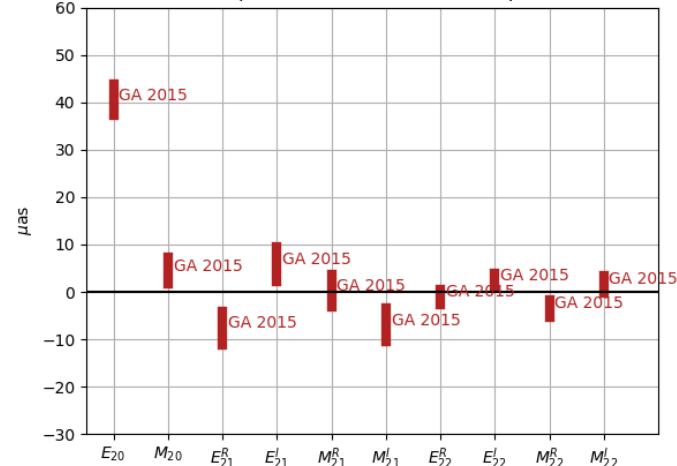
ICRF3
vs
ICRF2

ICRF3
vs
Gaia DR2

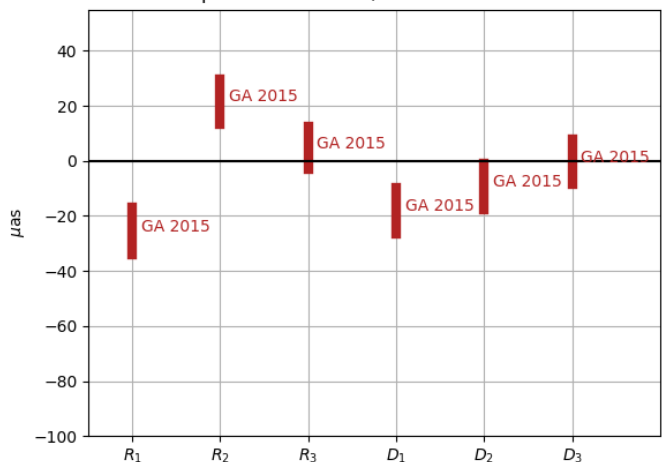
Comparison with ICRF2 / Orientation and Glide



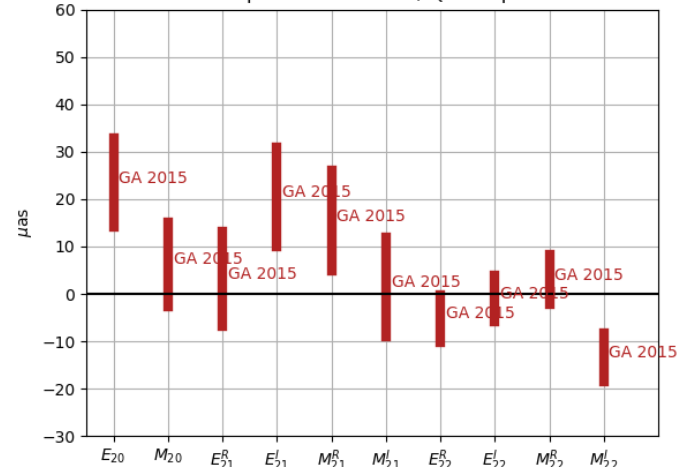
Comparison with ICRF2 / Quadrupole



Comparison with DR2 / Orientation and Glide



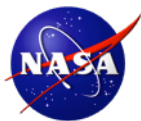
Comparison with DR2 / Quadrupole





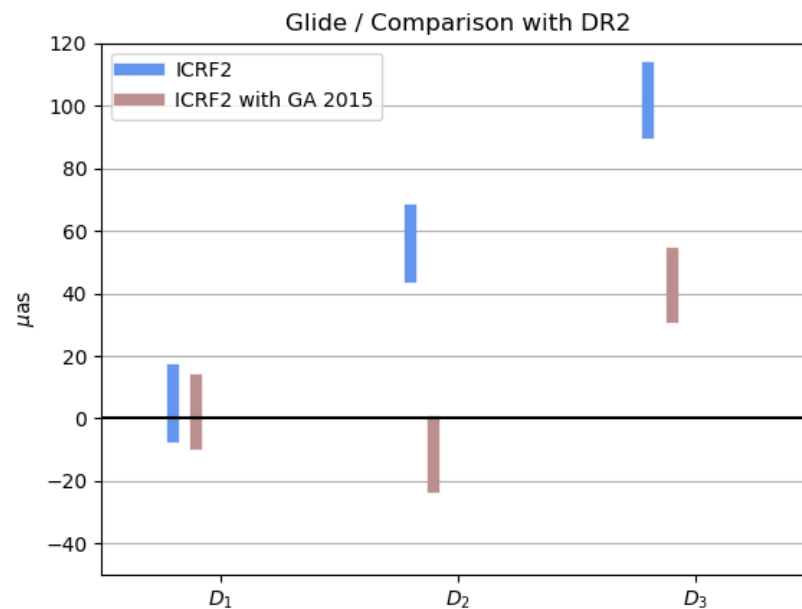
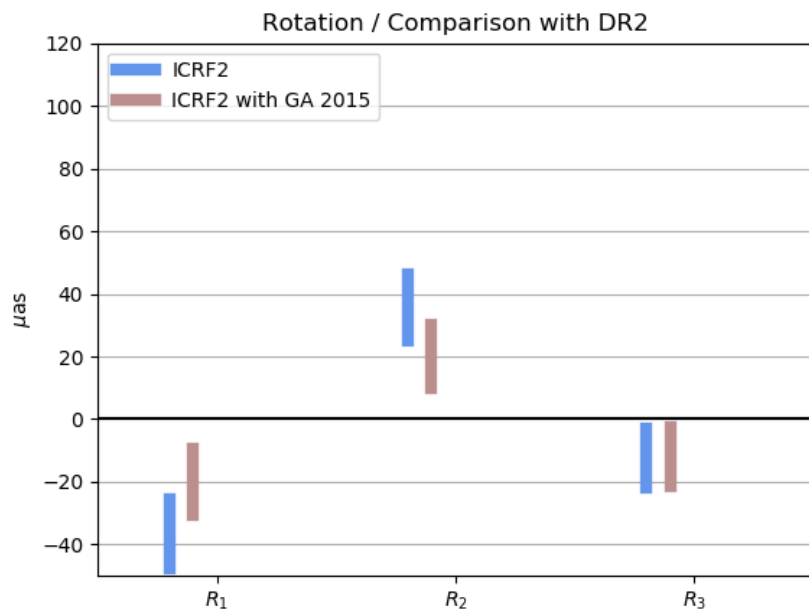
Summary of comparisons

- Comparison of ICRF3 and Gaia DR2 show no deformations larger than 20 μ as between the two catalogs
- Comparison of ICRF3 and ICRF2 show deformations up to 80 μ as between the two catalogs
- All indicates that systematics are in ICRF2, not in ICRF3 (unless Gaia DR2 and ICRF3 would be deformed in the same way)



Reproducing ICRF2...

... and correcting for Galactic aberration



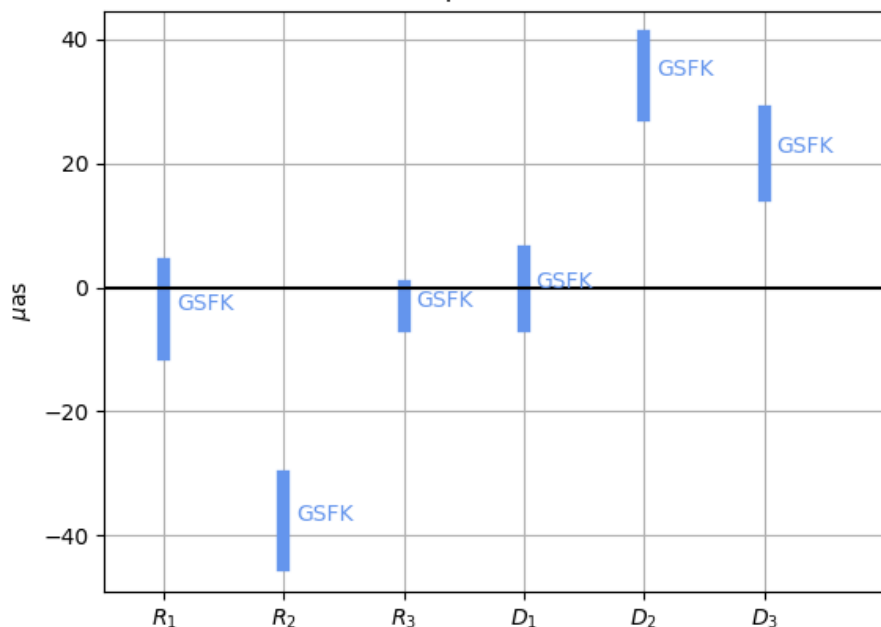
... removes the bias in D2 and reduces the bias in D3 by 60%



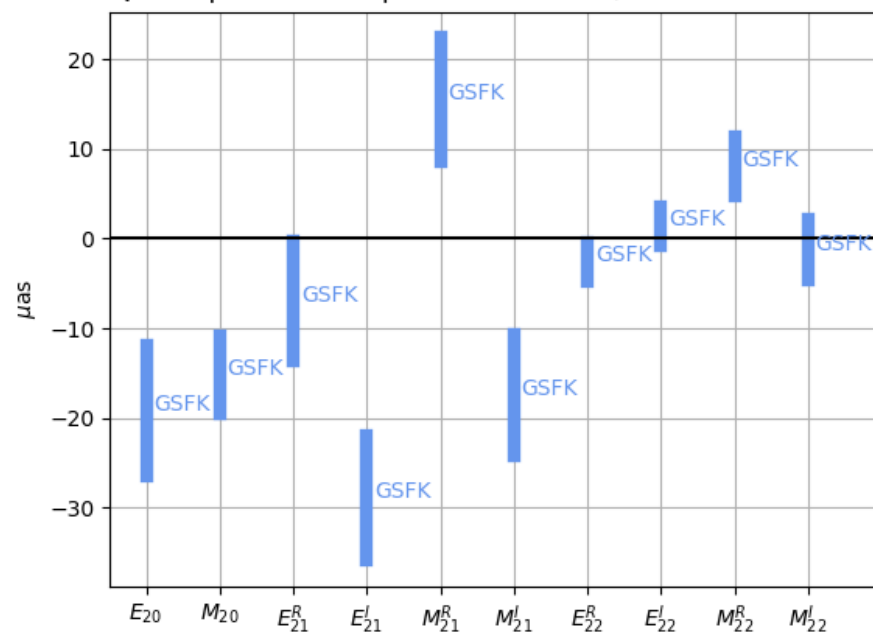
K (24 GHz) vs. SX (8 GHz)

Independent VLBI data sets provide checks

Orientation and Glide wrt Comparison K minus S/X for GSFC Solution



Quadrupole wrt Comparison K minus S/X for GSFC Solution



Spherical Harmonic differences generally $< 35 \mu\text{as}$.

Rotation Y needs investigation.



Summary of the main features of ICRF3

- Incorporates 12 millions VLBI observations (about twice as much compared to ICRF2)
- Includes 30% more sources than ICRF2
- Most importantly: has a much more uniform distribution of position errors than ICRF2
 - Thanks to the re-observation of the VLBA Calibrator Survey in 2014-2015 and the « aggressive » program conducted with the VLBA since 2017 (under USNO time) which re-observed all the least-observed sources
- Is a multi-frequency frame
 - Primary positions at S/X band
 - Complementary positions at K band and X/Ka band for 600+ sources (positions not combined in order not to hide any real physical effects)
- Incorporates Galactic aberration
- Has no significant deformations relative to Gaia DR2



Release of ICRF3

- ICRF3 to be submitted for publication in a journal paper
- ICRF3 to be presented for adoption at IAU General Assembly (Vienna, 20-31 August 2018)
 - IAU resolution already submitted (15 February 2018)
- ICRF3 to be released by the time of IAU General Assembly.